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REPORT

Voltage breakdown in u.h.f. feeders and combining equipment

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Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

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VOLTAGE BREAKDOWN IN U.H.F. FEEDERS AND COMBINING EQUIPMENT

Summary

The peak voltage in a transmitter feeder carrying four vision and four sound carriers exists for only about 2% of the total operating time, in the form of very short pulses (of about 10 nanoseconds duration). It is reasonable to expect that the rating of feeders and associated equipment need not be specified to withstand the peak voltage under these conditions. The findings of this report indicate that a transient peak level about 60% in excess of the steady voltage rating could be tolerated without risk of damage.

1. Introduction

One of the problems encountered in the engineering of high-power u.h.f. television transmitting stations is that parts of the aerial feeder system, including filters, combining units etc. must carry a number of television signals at high power. In the cases where four-channel aerial systems are employed this equipment will eventually handle four vision and four sound carriers simultaneously. The three principal considerations for the specification and design of feeders and coaxial circuits at u.h.f. are copper-loss heating (particularly at standing-wave current maxima), dielectric loss (with possible over-heating) and voltage breakdown due to ionisation. Conductor heating is readily calculable, and dielectric heating can be eliminated by the use of suitable materials or other techniques. When a number of carriers are present together the estimation of the voltage breakdown threshold is much more difficult than when a single carrier is present under the same conditions. (Experiments to determine voltage breakdown cannot be scaled conveniently; the full power must be used). This report looks at some aspects of the voltage breakdown problem with multiple carriers and suggests some tentative conclusions.

2. The characteristics of a linear sum of sinusoids

Two distinct (but related) periodicities can be ascribed to the linear sum of a set of sinusoids. The sum of N sinusoids of frequencies f_1, f_2, f_3 ..... f_N* (any amplitude and phase) has a waveform with a period equal to that of the h.c.f. of the N frequencies. Providing the $(N - 1)$ difference frequencies $(f_2 - f_1)$, $(f_3 - f_1)$ etc. are all small compared with the least of the f's, the sum also exhibits an envelope with the period of the h.c.f. of the $(N-1)$ difference frequencies. (The basic period is an integral multiple of the envelope period). If it so happens that all the sinusoids have their maximum positive (or negative) values at the same instant, the maximum peak voltage occurs.

As an example consider a set of carriers corresponding to the vision and sound frequencies of the typical channel group 40, 43, 46 and 50. (Vision carriers 623·25, 647·25, 671·25 and 703·25 MHz; sound carriers 629·25, 653·25, 677·25 and 709·25 MHz.) Initially we suppose that these carriers are unmodulated, the vision carriers having their peak value which in practice only occurs during synchronising pulse periods of the modulating video waveform.

*The f's are assumed to be rational numbers.

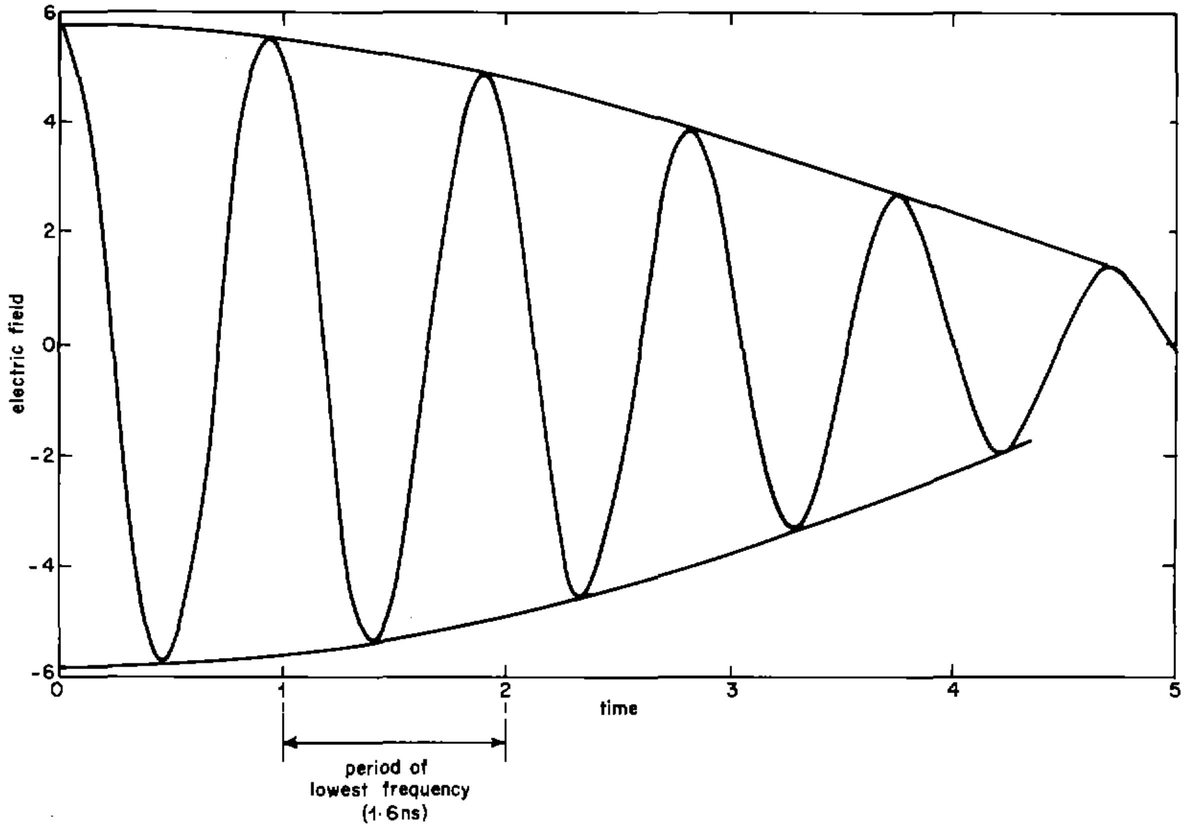

Fig. 1 - R.F. waveform (the resultant of 4 vision and 4 sound carriers of the channel group 40, 43, 46, 50) during the 8 ns period immediately following the peak when all 8 carriers are additive

The four vision carriers will be assumed to have equal peak amplitudes. The four sound carriers are also assumed to have equal peak amplitudes – 7 dB relative to the vision carrier peak amplitude. Fig. 1 shows the voltage waveform of the group just after the positive peaks come into coincidence. It will be seen, after the maximum value occurs, that the peak amplitude drops to only 25% of maximum within five cycles of the lowest carrier frequency (623·25 MHz).

In the transmission of a negatively modulated television signal the peak vision carrier amplitude only occurs during synchronising pulse periods. Line synchronising pulses have a duration of about 5 μSec, so that a number of peaks can occur during one line synchronising pulse. The situation shown in Fig. 1 will only occur in practice, therefore, if the peaks of all the carriers occur at the same instant, and the synchronising pulses coincide. The peaks of interest (i.e. those of greatest magnitude) occur during the line and field synchronising pulses.

3. Fundamental processes in a gas

At voltage breakdown the electric current in a gas is carried by free electrons, positive ions and negative ions. Charge carriers may be produced in a gas by molecular collisions (resulting from thermal agitation) cosmic radiation or impact ionisation (the collision between a charge carrier and a molecule to release a further carrier). Thermal agitation and cosmic radiation give rise to a low threshold level of ionisation. Impact ionisation becomes appreciable when the gas is in a strong electric field and is the process which is responsible for the rapid increase in charge carriers as the electric field in the gas is increased. When a gas is subjected to an increasing electric field, a point will be reached when the de-ionisation process (diffusion, recombination and attachment) will be unable to remove the charge carriers as fast as they are being created, and the gas will break down.

Whereas the ionisation processes all create charge carriers by providing the energy necessary to separate an electron from a gas atom, there are three distinct processes by which the carriers may be removed from the gas: diffusion, recombination and attachment. Charge carriers may be removed from the region of high electric field by diffusion to a region of low field or to the walls of the container, where they are discharged. In the case of an open-wire feeder, most of the carriers removed by diffusion would leave the gap between the feeder elements and move into a region of lower field. Carriers in a coaxial feeder, having no access to a region of lower field, diffuse to the walls (which are also the elements of the feeder) and are discharged. Recombination occurs when an electron and a positive ion encounter each other and the electron is captured by the ion to form a neutral atom. Certain gases also exhibit attachment, whereby an electron may be attracted by a neutral atom to form a negative ion. The negative ion has a much lower mobility than the electron and consequently contributes very little to the conductivity of the gas.

Fundamental processes in gases are dealt with in references 1, 2 and 3. Thermal effects, which have been mentioned in this section, are treated in references 7 and 8. Reference 7 also contains information on the effects of filling feeders and resonators with different gases.

The calculations in this report are based largely on kinetic theory, and references 4 and 5 are recommended for their treatment of this subject.

4. Geometry

The voltage level at which electrical breakdown occurs in a gas depends critically on the shape of the conductors; that is it depends on the voltage gradient configuration. The two cases where the conductors comprise parallel plates and a plate and a needle point typify the extremes of the geometrical spectrum. Not only is the breakdown voltage much lower in the latter case (for the same gas at the same temperature and pressure with the same spacing, owing to the intensification of electric field) but the formation of the conducting path, or paths, through the gas follow a different pattern which itself varies according to whether the point is charged positively or negatively with respect to the plate.

5. The built-up of electron density in a uniform, constant field

Before breakdown takes place in a gas the density of free electrons in the region of maximum gradient between the electrodes achieves a critical value. As the electron density increases the gas acquires an increasing space charge caused by the relatively slowly moving positive ions being left behind while the electrons move away. The space charge causes concentrations of the field in certain regions,[6] facilitating multiplication until, at the onset of breakdown, multiplication proceeds at an increasing rate even if the field ceases to increase. This process leads to the formation of current-carrying filaments throughout the gas. If the applied voltage is too low to cause the critical density to be reached, breakdown does not occur.

If certain simplifying assumptions are made the free electron density in a gas subject to a uniform electric field, before breakdown, can be expressed by means of a first-order differential equation viz.

$$\frac{dn}{dt} = \alpha n - \beta n^2 \qquad (1)$$

n = density of free electrons

α = ionisation coefficient, function of the voltage gradient

β = re-combination constant

The rate of increase of free electrons is proportional to the concentration of free electrons already present as shown by the first term on the r.h.s. of the equation. If free electrons are removed only by re-combination with positive ions, the rate of re-combination is proportional both to the density of free electrons and to the density of positive ions, i.e. proportional to n^2 as shown by the second term on the r.h.s. of the equation.

The omission from equation (1) of terms representing diffusion and attachment could give rise to errors. However, it is felt that the omission of diffusion is justified on the ground that the feeder spacing is large compared with the diffusion length of electrons in air at atmospheric pressure.[2] Attachment depends on the nature of the gas in the feeder, and is proportional to the density of electrons present (n). For air, however, attachment is not significant and need not be considered.

The value of β, the re-combination coefficient, can be obtained from physical data (e.g. in Kaye and Laby's Tables). The parameter, α, the ionisation coefficient, is a function of the electric field in the gas. The expression for α, as a function of the applied field, will have the same general form as Townsend's first ionisation coefficient.[1,2,5] For air at N.T.P. the approximate formula for α is assumed to be,

$$\alpha = 3{\cdot}18 \times 10^{12}\, e^{-4 \times 10^7/E}\ \mathrm{sec}^{-1} \quad \text{(See Appendix I)} \qquad (2)$$

where E is the field in Volts/m.

This expression for α is derived from kinetic theory, and assumes that the energy gained by a free electron from the electric field is lost to the gas molecules on a collision irrespective of whether a fresh ion-electron pair is created or not. The coefficient α increases rapidly with the field, and Fig. 2 shows α as a function of E in the region of breakdown (i.e. for value of E close to the breakdown field for air between plane parallel electrodes). The solution to

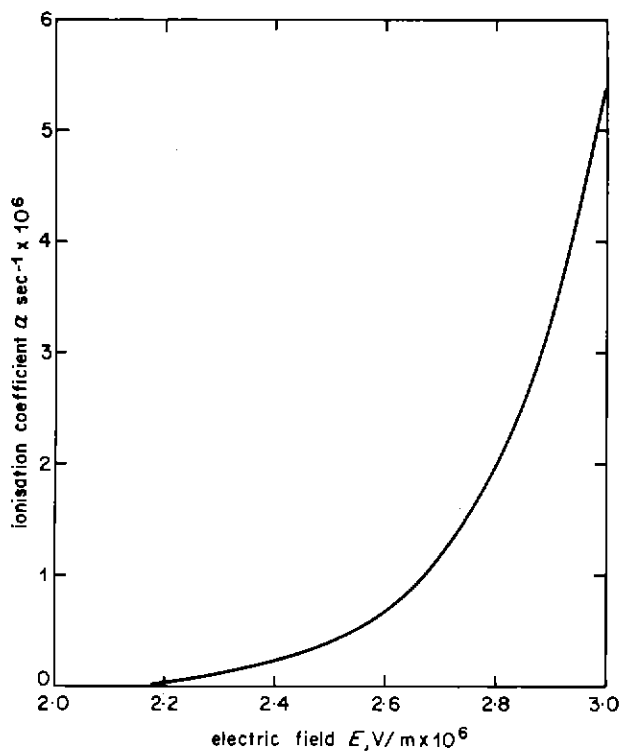

Fig. 2 - Ionisation coefficient as a function of electric field in air

the differential equation (1) when a constant voltage is applied at $t = 0$ is

$$n = \frac{K}{1 + (K/n_0 - 1)e^{-\alpha t}} \qquad \text{(See Appendix II)} \quad (3)$$

where n_0 = density of free electrons at time $t = 0$

and $K = \alpha/\beta$

6. The effect of applying a radio-frequency field

For a sustained r.f. voltage, the field which a gas will withstand is independent of frequency up to about 250 GHz. At this frequency, the period of oscillation of the free electrons is approximately equal to the mean free time between collisions. Above 250 GHz the breakdown voltage increases with frequency.[7]

A possible approach, therefore, is to neglect the r.f. nature of the waveform and to consider the feeder to be carrying the waveform of Fig. 3 which is a simplified d.c. equivalent of the r.f. envelope waveform for the 8 carriers described in Section 2. It is assumed that all the carriers have constant amplitude corresponding to the maximum possible values. In the case of four television signals with their associated sound signals such a condition would only occur during synchronising pulse periods and then only if these periods were coincident. The level E_1 of the waveform represents the peak r.f. field when all carriers are added in phase, whilst the low field period is represented by the level E_2.

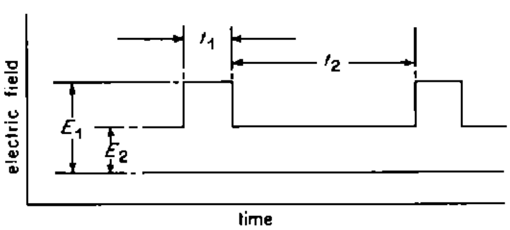

Fig. 3 - Simplified d.c. waveform taken to represent periods of peak voltage and lower voltage in a feeder

In order to calculate the conditions necessary for breakdown of the gas, let the free electron density at the threshold of a discharge be N, and α_1 be the ionisation coefficient corresponding to a field E_1, α_2 corresponding to E_2. After a number of repetitions of the waveform in Fig. 3, the density of free electrons in the gas at the end of the r+1th interval is given by:

$$n_{r+1} = \frac{K_1}{1 + \left(\frac{K_1}{n_r} - 1\right) e^{-\alpha_1 t_1}} \qquad \text{from (3)}$$

(Note that periods r and r+2 are of duration t_2, r+1 of duration t_1).

The free electron density at the end of r+2th period is given by:

$$n_{r+2} = \frac{K_2}{1 + \left(\frac{K_2}{n_{r+1}} - 1\right) e^{-\alpha_2 t_2}} =$$

$$= \frac{K_1 K_2 n_r}{n_r K_1 (1 - e^{-\alpha_2 t_2}) + [n_r + (K_1 - n_r) e^{-\alpha_1 t_1}] K_2 e^{-\alpha_2 t_2}} =$$

$$= \frac{A n_r}{B n_r + C} \qquad (4)$$

Where $K_1 = \alpha_1/\beta$, $K_2 = \alpha_2/\beta$

$A = K_1 K_2 > 0$

$C = K_1 K_2 e^{-\theta} \quad \theta = \alpha_1 t_1 + \alpha_2 t_2$

$B = K_1 (1 - e^{-\alpha_2 t_2}) + K_2 (e^{\alpha_2 t_2} - e^{\theta}) > 0$

From (4) the increase in free electron concentration from the end of the rth period to the end of the r+2th period (i.e. over a whole cycle) is given by:

$$n_{r+2} - n_r = n_r \left\{ \frac{A - (B n_r + C)}{B n_r + C} \right\}$$

$$= n_r \left\{ \frac{(A - C) - B n_r}{B n_r + C} \right\} \qquad (5)$$

When the free electron concentration has reached its limiting value (assuming that breakdown does not occur), $n_{r+2} - n_r = 0$ which implies that $(A - C) - B n_l = 0$ where n_l = limiting concentration of free electrons.

$$\therefore \quad n_l = \frac{A - C}{B} = \frac{K_1 K_2 (1 - e^{-\theta})}{K_1 (1 - e^{-\alpha_2 t_2}) + K_2 (e^{-\alpha_2 t_2} - e^{\theta})} \qquad (6)$$

Substituting the conditions of breakdown in (6) above, a figure is obtained for the free electron concentration N at the instant when breakdown is initiated. (β for air is approx. $1{\cdot}6 \times 10^{-6}$ cm³/sec, breakdown field taken as a sustained electric field of 3×10^6 V/m).

The free electron concentration obtained from the calculation is $3{\cdot}34 \times 10^{12}$ free electrons/cm³, and flashover is extremely unlikely to occur if n remains below this value throughout the gas. Concentrations of this order have been found by Meek and Craggs[1] in air at the threshold of breakdown.

It is permissible for a field in excess of the breakdown value to exist in the feeder, provided that the time for which such a field is present is restricted so that the critical concentration of electrons (N) is not reached. In this case, the period for which only a relatively low field

exists must be sufficient for the recombination of the excess free electrons, otherwise successive high-field pulses will eventually give rise to the breakdown condition.

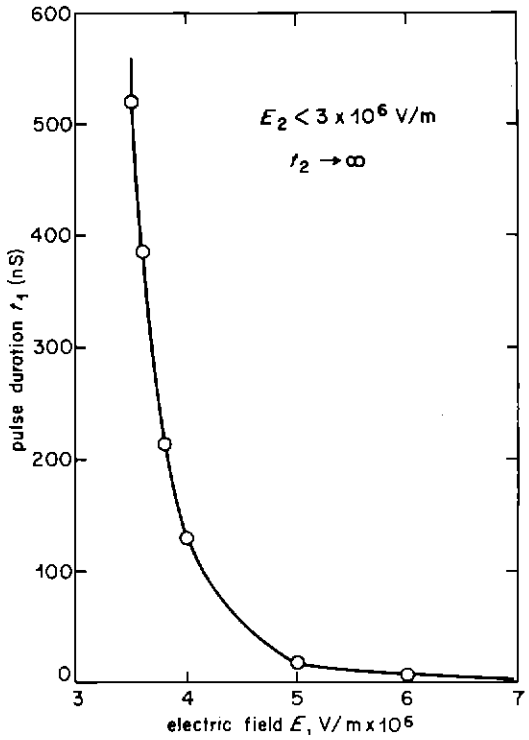

Fig. 4 - Maximum pulse duration for breakdown not to take place, as a function of electric field during the pulse (in air)

The graph of Fig. 4 shows the maximum duration of an isolated pulse as a function of the peak field produced by the pulse. Fig. 5 shows the relationship between maximum ratio of pulse duration to the time between pulses and to the peak field in the case of repetitive pulses. For these graphs it has been assumed that E_2 is equal to the r.m.s. field (approx. 40% of E_1) and, for Fig. 5, that the peak field pulse lasts for about 10nS (see Fig. 1).

On the basis of these calculations (and assumptions) an estimate may be made of the peak voltage which a feeder would be able to withstand. Calculations of the waveform resulting from the combination of the 8 carriers indicate that the peak pulse duration is about 10nS, and that the time between the highest peaks is 500nS, and the feeder would be expected to withstand an r.m.s. r.f. voltage 66% in excess of the rated d.c. breakdown level during the 10 nS pulse (this figure is calculated using equation (6)). From Figs. 4 and 5 it can be verified that a pulse of this magnitude lasting for 10nS with a period of 500nS before the next high-field pulse is insufficient to cause breakdown.

7. Gases of high dielectric strength

It is possible to raise the breakdwon foltage of feeders and combining units by replacing the air in them with a gas of high dielectric strength. The gas would need to be pressurized so that any leaks would result in seepage of the

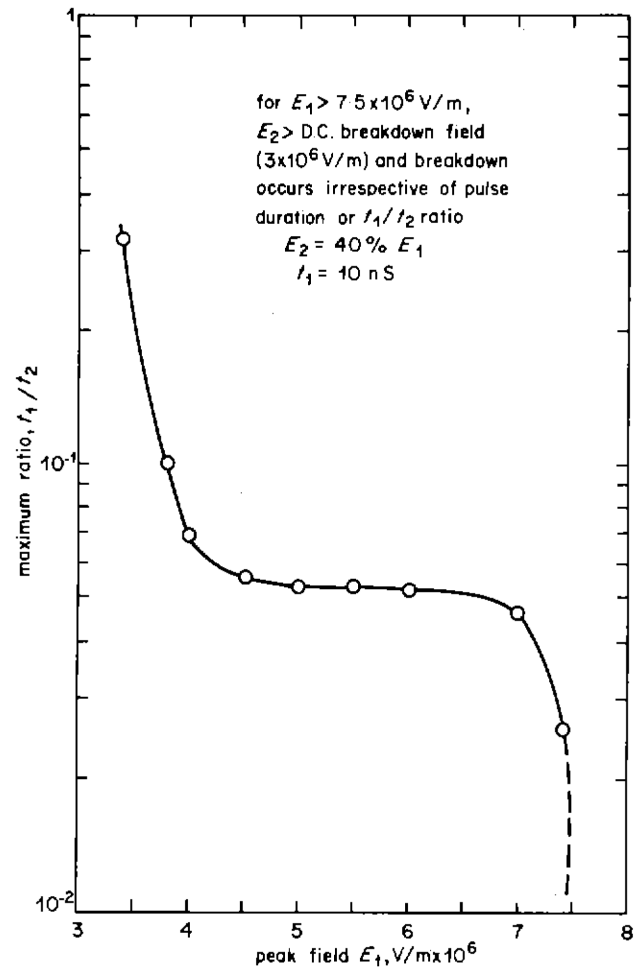

Fig. 5 - Maximum ratio of pulse duration (t_1) to low-field period (t_2) as a function of peak field, for no breakdown to occur (in air)

gas from the feeder rather than air into the feeder.

Helium would be a suitable gas, having an ionisation potential twice that of air, but as its cost is high (about fifty times that of nitrogen) it could only be used economically to protect a limited part of the feeder equipment, such as the filterplexer. Leakage from a relatively long section of feeder would prove so expensive as to prohibit the use of helium on a large scale.

Gases exhibiting a high degree of attachment have been developed specifically for the purpose of insulation, and the use of "Freon" or "Arcton" gases* would increase the *power* rating of a feeder by six times. In the event of a discharge occuring, both gases decompose to form toxic substances and the insulating properties of the gases are destroyed. Extensive purging of the feeder system would then be necessary before transmissions could be resumed.

8. Conclusions

The simple mathematical treatment presented in this paper gives results which would indicate that a feeder

*Freon is made by Dupont, and Arcton by ICI.

handling four u.h.f. television programmes will withstand a peak voltage approximately 66% in excess of its steady voltage rating. It must be stressed, however, that this result is only an estimate as the calculations embody a number of approximations. In the first instance, a uniform electric field has been assumed to exist throughout the feeder. This condition would only be obtained between parallel plates and in the absence of any appreciable number of free electrons, although a large-diameter coaxial feeder of the type used at transmitters represents a reasonable approximation to the parallel-plate feeder. Secondly, the electron removal mechanisms of attachment and diffusion have been ignored, on the grounds that the effects of these are small in the conditions considered. It should be realised, however, that the approximations which have been made tend to lead to a conservative estimate of the permissible increase in rating.

If more accurate results are required a practical investigation would be necessary, although it must be explained that difficulties arise when attempts are made to scale the feeder dimensions and operating conditions down to a level suitable for laboratory experiments.

Finally, some mention should be made of thermal effects. It is observed that when the temperature of a gas rises, its breakdown voltage is reduced proportionally with the absolute temperature (see Ref. 7, p. 908 and Ref. 8, p. 921). As a result some cooling of high-power feeders and associated equipment may prove necessary.

9. References

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APPENDIX I

The ionisation coefficient, α

α is defined as
(mean collision rate) x (probability of an electron acquiring ionising potential before collision)

Let $P(t)$ = probability that an electron remains free (i.e. does not suffer a collision) for time t.

We put $dP = -\dfrac{P\,dt}{\bar{t}}$

where $\bar{t}$ is mean free time (i.e. mean time between collisions) = (mean collision rate)$^{-1}$

Hence $P = e^{-t/\bar{t}}$

Therefore for air at N.T.P. $\alpha = \dfrac{1}{\bar{t}} e^{-t/\bar{t}}$, where t = $\dfrac{1{\cdot}28 \times 10^{-5}}{E}$ secs is the free time necessary in field E for electrons to acquire ionisation potential.

$\bar{t} = 3{\cdot}14 \times 10^{-13}$ sec. for field-free air at N.T.P., and this value is substantially unaltered for air in which fields sufficient to cause breakdown are present.

Substituting in the expression for α, we obtain:—

$$\underline{\alpha = 3{\cdot}18 \times 10^{12}\, e^{-4\times10^{7}/E} \text{ sec.}^{-1}}$$

This result is based on the assumption that the ionising process is 100% efficient. This will tend to lead to a conservative estimate of the permissible increase in the rating of the feeder.

APPENDIX II

Solution of the differential equation (1)

The rate of increase in free electron density in the gas is represented by

$$\frac{dn}{dt} = \alpha n - \beta n^2$$

In order to obtain an expression for the free electron density, the equation is rearranged and integrated:—

$$\int_0^t dt = \int_{n_o}^{n} \frac{dn}{\alpha n\left(1-\frac{\beta n}{\alpha}\right)} = \frac{1}{\alpha} \int_{n_o}^{n} \left(\frac{1}{n}\right)\left(\frac{1}{1-\frac{\beta}{\alpha}n}\right) dn$$

(boundary conditions are $n = n_o$ at $t = 0$)

$$= \frac{1}{\alpha}\int_{n_o}^{n} \frac{dn}{n} + \frac{1}{\alpha}\int_{n_o}^{n} \frac{\left(\frac{\beta}{\alpha}\right)}{\left(1-\frac{\beta n}{\alpha}\right)} dn$$

$$= \frac{1}{\alpha}\log_e\left(\frac{n}{n_o}\right) - \frac{1}{\alpha}\log_e\left(\frac{1-\frac{\beta n}{\alpha}}{1-\frac{\beta n_o}{\alpha}}\right)$$

i.e. $$\alpha t = \log_e\left(\frac{n\left[1-\frac{\beta}{\alpha}n_o\right]}{n_o\left[1-\frac{\beta}{\alpha}n\right]}\right)$$

$$n - \frac{\beta}{\alpha}n_o n = \left(n_o - \frac{\beta}{\alpha}n_o n\right)e^{\alpha t} = n_o e^{\alpha t} - \frac{\beta}{\alpha}n_o n e^{\alpha t}$$

Putting $K = \dfrac{\alpha}{\beta}$

$$n = \frac{n_o e^{\alpha t}}{1-\frac{\beta}{\alpha}n_o(1-e^{\alpha t})} = \frac{K}{1+\left(\frac{K}{n_o}-1\right)e^{\alpha t}}$$